Augmented reality for the engineering of collective behaviours in microsystems

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***Abstract*— Microsystems composed of responsive particles or even living cells often operate in large numbers to perform tasks beyond the capabilities of each individual. Engineering collective behaviours in such systems could lead to breakthroughs in medicine, or entirely new applications. Key to many collective behaviours is the ability for micro-agents to communicate with their neighbours through chemical signaling, energy transfer (e.g. heat), or modification of the environment (stigmergy). However, implementing such communication modalities is typically challenging and time consuming. To simplify this process, we propose to use augmented reality (AR) to implement a new form of communication channel using light. Our AR Dynamic Optical Micro-Environment (AR Dome) is able to provide micro-agents with varying communication ranges and the ability to modify their environment in complex ways. AR is achieved through a custom made closed-loop system based on an ultra violet (UV) light projector and imaging apparatus. Using AR DOME, we show how micro-particles can be endowed with new communication capabilities and demonstrate propagation of an AR-based light communication signal through a population of micro-particles.**

I. INTRODUCTION

Collective behaviours often emerge from simple interactions between agents and their environment [1]. Engineering these behaviours has become a key area of focus in swarm engineering [2]. Crucial to their emergence is the ability to implement communication between agents and their local environment [3], [4]. Engineering collective behaviours at a microscopic scale shows clear opportunities, both because of the large numbers of individuals that are typically involved (e.g. millions of bacteria in a biofilm), and the limited capabilities of individual agents which may benefit from emergent swarm intelligence [5]. Applications range from engineering collective nano- or micro-agents to improve drug distribution in cancer therapy [6], to designing synthetic bacterial architectures through morphogenesis [7].

While implementing communication at these scales is feasible using the diffusion of chemicals [8], energy [9], or environmental modifications [10], [11], achieving a desired specification in reality is often the result of many years of research. As a stepping stone, in this work we implement a novel and highly controllable communication channel between micro-agents using augmented reality (AR). The AR system presented is an example of spatial AR, a subset of AR in which patterns or objects are projected directly onto real physical space [12]. Spatial AR systems typically consist of a projector, camera and computing device [13], [14]. Potential controllable micro-agents include engineered light-reactive cells [15], [16], micro-particles [17], or other forms of active matter [18]. A detailed review of light-controlled tools and motors is provided by Brieke *et al* [19] and Eskandarloo *et al* [20]. In our system, communication is performed using light halos projected around micro-agents. Other micro-agents can then react to these light signals by changing their behaviour, for example by moving, self-assembling, or by generating their own communication signals (Fig. 1).

We chose light as a communication modality because it is easy to control at a high-resolution in space and time [21]. In particular, we use an off-the-shelf digital light projector (DLP), which can easily be modified to emit a desired wavelength of light, and integrate this into a custom-built imaging device. Here we chose ultra violet (UV) light due to its potential in supporting interesting particle responses with chemically modified surfaces (e.g. cleavage/detachment of anchoring molecules [22]). A camera captures the experimental field of view containing both the micro-agents and their projected communication halos. The result is a visual image that can be analysed in real-time using widely

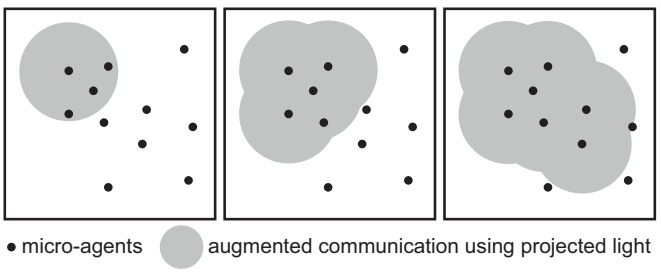

Fig. 1: Schematic representing augmented reality (AR). Communication signals are projected as light halos around micro-agents. Neighbouring micro-agents that fall within this light halo then react by changing their behaviour, for example by generating their own communication signal (produced by the AR system). This leads to propagation of the communication signal through the population.

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available image processing tools such as OpenCV [23]. Dynamically updating the communication halos is then done by changing the projected UV image, allowing for closed-loop feedback control of AR for the micro-agents. Similar DLP setups have been used in the past to control bacteria-coated microplates [24] and light-responsive bacteria [15]. Light has also widely been used to control cells through optogenetics [25], as well as manipulate microsystems through optical trapping [26]. Beyond light, the control of micro- and nano-swimmers has also been proposed using magnetic fields, ultrasound, temperature, light, and chemical gradients [27]. Past work, however, has not used AR to add new capabilities (i.e. communication) to micro-agents.

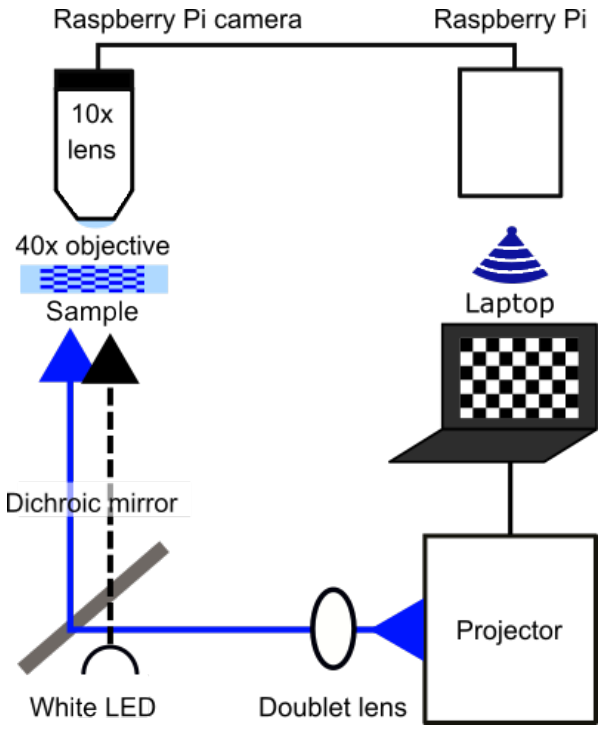
In the following sections, we present the design of the experimental setup for closed-loop control of the AR DOME and its calibration. We demonstrate our system's use through the automatic projection of different sized communication halos around micro-particles, and provide a proof of concept approach for implementing information propagation through a population of micro-particles which have no inherent communication capabilities.

II. METHODS AND MATERIALS

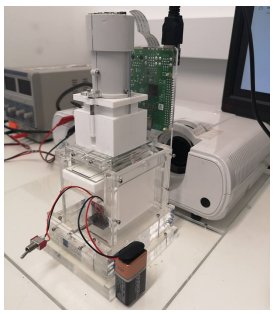
A. AR DOME setup

The AR DOME is a custom-built closed-loop system (Fig. 2a,b) for the control of light-based AR. It is composed of a DLP (Mitsubishi XD221U), modified to project UV light patterns by replacing the light source with a four UV LED array $\lambda_{max} = 370$ nm (LZ4-44UV00-0000, LedEngin Inc). The light patterns are 1024×768 pixel binary images, where a white pixel has UV illumination and a black pixel doesn't. Output from the DLP was controlled through a visible achromatic doublet pair lens of magnification 1:1 (MAP104040-A, Thor Labs), and a 490 nm longpass dichroic mirror (DMLP490R, Thor Labs) to enable projection onto a stage where a sample is placed, which is imaged at a 400X magnification using a Raspberry Pi 3 model B with camera module v2. The dichroic mirror also acts as a beam combining lens, allowing global illumination from a white backlight. Spectral analysis of the light output provided to the sample after passing through the DLP and optics was performed using a calibrated spectrophotometer (QE65000, Ocean Optics, Largo, USA), with the optical fiber positioned above the dichroic mirror. A normalised intensity plot comparing these results to the same analysis performed on the raw LED light source shows a shift in peak wavelength to 393 nm (Fig. 2c). This peak shift could be exploited to work with systems that respond to both UV and blue wavelengths, as well as for fluorescence imaging with green fluorescent protein, which has a major excitation peak at 395nm[28]. A video stream is established on the Raspberry Pi using VLC player, allowing remote connection to the camera feed by a computer (Dell Latitude e5470). The stream is processed using a Python script which accesses the IP address of the Raspberry Pi, and analyses the video frame by frame. Analysis is performed using the OpenCV library [23], specifically using thresholding and contour location functions to find distinct objects within the camera field of view. This script analyses the current image from the camera and sends a new UV light pattern to provide the required closed-loop AR; in this case, projecting halos of $\lambda_{max} = 393$ nm light around particles as an augmented communication signal.

Fluorescent polystyrene beads (FluoSpheres, Invitrogen) with a 10 μm diameter were chosen as static micro-agents for use in all our experiments. These were diluted in water



(a)



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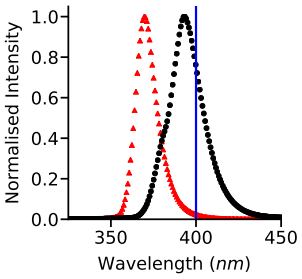

(c)

Fig. 2: (a) Schematic of the closed-loop AR DOME setup consisting of a modified DLP, custom magnification and filter optics, and a Raspberry Pi controlled camera streaming to a laptop for image processing and projection. (b) Image of the physical experimental setup. (c) Normalised intensity spectra of the raw LED light output (red triangular markers) and the DLP light output measured at the sample stage using a spectrometer (black circular markers). The wavelength cut off between UV and blue light at 400 nm is marked by a solid blue line.

and deposited on a glass slide with cover slip for imaging (Fig. 3a).

B. Calibration of the system

Before using the AR DOME, it is first necessary to calibrate the alignment of the DLP output onto the field of view such that individual particles can be accurately illuminated. Such a transformation is essential for robust closed-loop control to account for the non-linear effects in the optics and ensure accurate illumination of individual objects over the course of an experiment. This should be achievable in the shortest time possible, so that a re-calibration mid-experiment is feasible. As the projection area is over 100 times larger than the microscope camera field of view, a pixel by pixel search to find the area of focus would be slow and inefficient. Therefore, to rapidly locate the central pixel, a hierarchical search is performed whereby the entire projected pattern is first split into four quarters with only one being fully illuminated (Fig. 3b, left panel). If the lit area covers the central pixel in the field of vision, then this quarter is further split into quarters, again with only one illuminated. If the central pixel is not lit, then the next quarter in the region is illuminated until a hit is found. This divide and conquer algorithm runs recursively until a single pixel in the centre of the field of vision is illuminated by the DLP (Fig. 3b, left to right panels). Next, a 3×3 grid is projected around the central pixel (Fig. 3c) with each point in the grid being the illumination of a single pixel. This image is converted to grayscale and a threshold of 25 gray value is applied. This projected grid is then used to seed the calculation of a mapping from the DLP's output pattern and the corresponding location of each pixel in the field of view of the Raspberry Pi camera (Fig. 3d). This mapping shows that the camera's field of view through the objective, comprising 130×130 pixels, contains a 13×13 pixels section of the total projection at one time.

III. RESULTS

To demonstrate the basic functionality of the closed-loop AR DOME, we began by using the OpenCV library to automatically isolate individual micro-particles and then projected UV light halos around these locations (Fig. 4a). We varied the radii of these halos between 1 and 2 pixels, characterised their shape by applying an illumination threshold (Fig. 4b), and produced illumination profiles through each micro-particle (Fig. 4c,d). These showed that halos are positioned at the area of the micro-particle, and display slight irregularities in the shape of the illuminated area, likely due to distortions in the optics.

As a proof of concept of more complex functionalities that our system could support, we implemented a form of AR-based communication where a light-based signal travels through a population of micro-particles. Communication depends on the spatial arrangement of the micro-particles and their augmented communication radius. In this scenario, one micro-particle is chosen as a source which "emits" a UV signal within a limited spatial range of ∼50 μm. If another micro-particle falls within the communication halo, they too start to "emit" their own signal allowing for propagation throughout a population. If more than one micro-particle falls within the signal, all of these will be selected to propagate the signal in the next step. The propagation of the communication signal is fully handled by the closed-

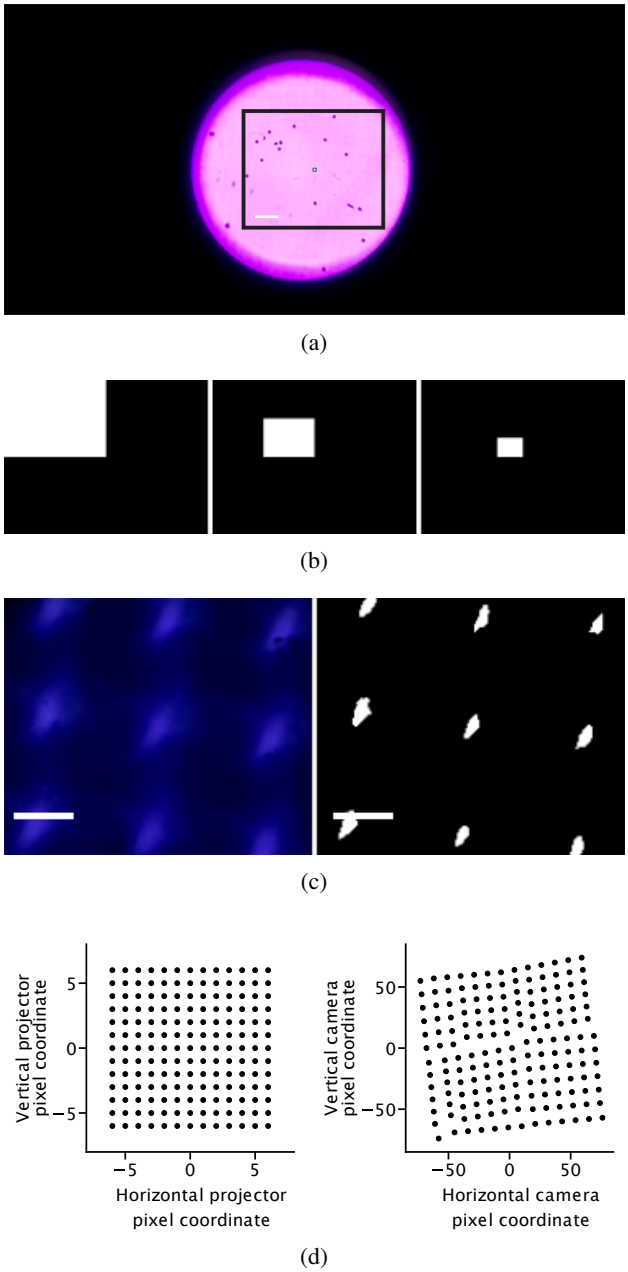

Fig. 3: (a) Micro-particles in the field of view of the camera before cropping to the region of interest indicated by a black box inside the image. (b) The first 3 frames projected in the divide and conquer calibration algorithm used to locate the center pixel. (c) Projected 3×3 grid before and after thresholding. (d) Mapping of each pixel projected (left) to the location at which it is detected by the camera (right). Scale bars represent a length of 80 μm.

loop control algorithm in the AR DOME, (Fig. 5a) and the same methodology could be directly applied to other forms of micro-agents, or even motile agents. Fig. 5b–g shows the propagation of the communication signal through a small population of micro-particles.

IV. DISCUSSION

In this work, we have shown how the AR DOME can allow static micro-particles to communicate using light. The small-scales involved require the precise control of tiny illuminated patches (pixels) from the DLP and their size poses limits to the size of micro-agents that can be used. With the current setup, the physical size represented by each pixel was measured using ImageJ to be 48×57 μm. To target the 10 μm particles with a halo closer to their size, or to target smaller particles altogether, focusing optics could be used to reduce pixel size. For agents larger than 50 μm, multiple pixels could be assigned to fully illuminate each agent.

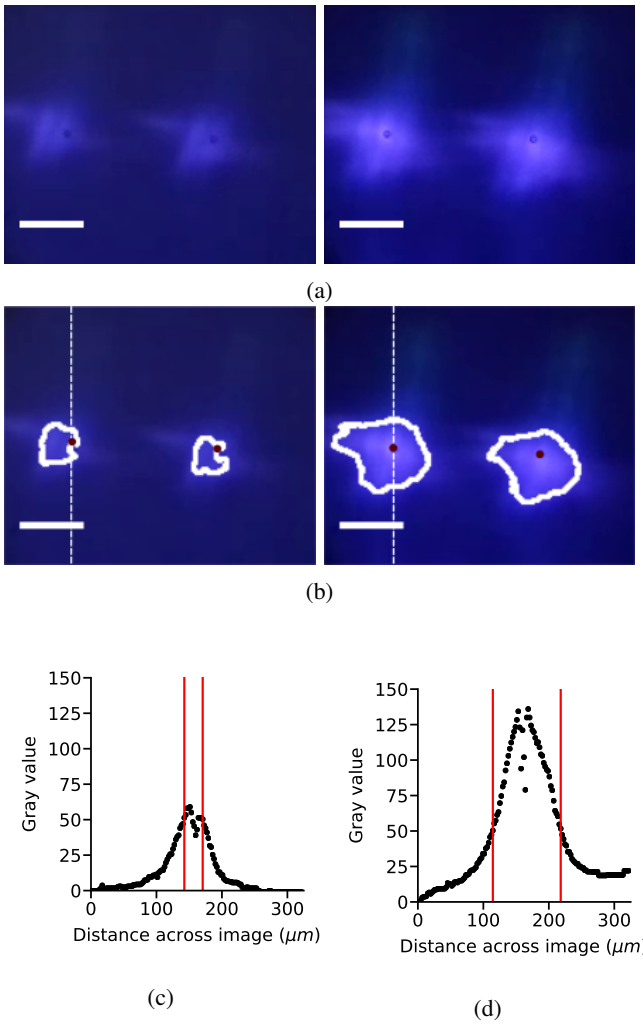

Fig. 4: (a) Halo projections onto two micro-particles of 1 pixel (left) and 4 pixels in a 2×2 grid (right). (b) Contours drawn onto images of halo projections show the change in halo radius, with the location of the micro-particles indicated by a red dot. (c) Gray pixel value plotted through a cross-section of the micro-particles for (c) 1 pixel projection and (d) 4 pixel projection using Fiji [29], indicated by white dashed lines in (b). Vertical red lines on the plot show the distance at which a gray value cut off of 50 is reached. Scale bars represent a length of 80 μm.

Another aspect of this system, important when applied to dynamic micro-agents, is the update speed of the AR DOME. At present, the limiting factor in the response time is the streaming and processing of frames collected by the camera. Theoretically, the standard Raspberry Pi camera software gives a camera speed of 30 fps, however this was slowed to 15 fps to reduce the processing burden. The current response time is on the order of a few seconds, which for a static system such as the micro-particles used here is sufficient. For a dynamic systems, this response time could also be effective. For motile bacteria with typical velocities below 20 μm/s, a response time of 2 seconds would on average allow the system to capture and process a microscope image, as well as create and send a new projection before the bacteria moved out of the 48×57 μm pixel area. For systems with higher velocities, the response time of this system may need to be improved. This could be done in a number of ways. To reduce the image processing load, we could lower the sampling rate in the processing code. However too large a reduction in sampling rate for a highly motile system could result in under sampling, and a loss of information. An alternative approach would be to perform the image processing on board the Raspberry Pi, massively reducing system response time by eliminating the video streaming component of the feedback loop.

V. FUTURE WORK

Using the AR DOME, one could already implement decision making algorithms [30], synchronised signaling [31], or patterning [32]. In the future, we aim to provide other modes of augmented communication, including depositing information (in this case light) in the environment (i.e. stigmergy) to enable indirect interactions between agents [4]. This would be done by leaving trails of light based on the activity/movement of a micro-agent, with other micro-agents reacting to these light signals — similar to ants depositing and reacting to pheromone. In the future, using micro-agents which are themselves responsive to the projected light would enable more complex collective behaviours. To this end, we will work with light-reactive micro-robots [33], bacteria [15], and micro-particles [17] to engineer swarm behaviours such as trail formation [34], phototaxis [35], and morphogenesis [36] at a microscopic scale. Using light as a localised signal allows for a high degree of spatio-temporal control over a microscopic system, something that can be difficult to achieve through external energy fields, chemical gradients and diffusive signals alone.

VI. CONCLUSION

Engineering collective behaviours in microsystems could enable new developments in fields ranging from cancer

therapy to synthetic biology. One key ability of collective systems is the ability to communicate between agents. To this end, we demonstrate how our AR DOME can be used to endow micro-agents with new light-based communication capabilities. In particular, we show the projection of UV light halos with two different radii, and use these halos to propagate a communication signal through a population of randomly positioned micro-particles. In the future, we will use the AR DOME to implement stigmergy, and to augment light-responsive micro-agents such as phototactic bacteria or light-activated micro-particles. This would allow more complex self-organised behaviours to emerge.

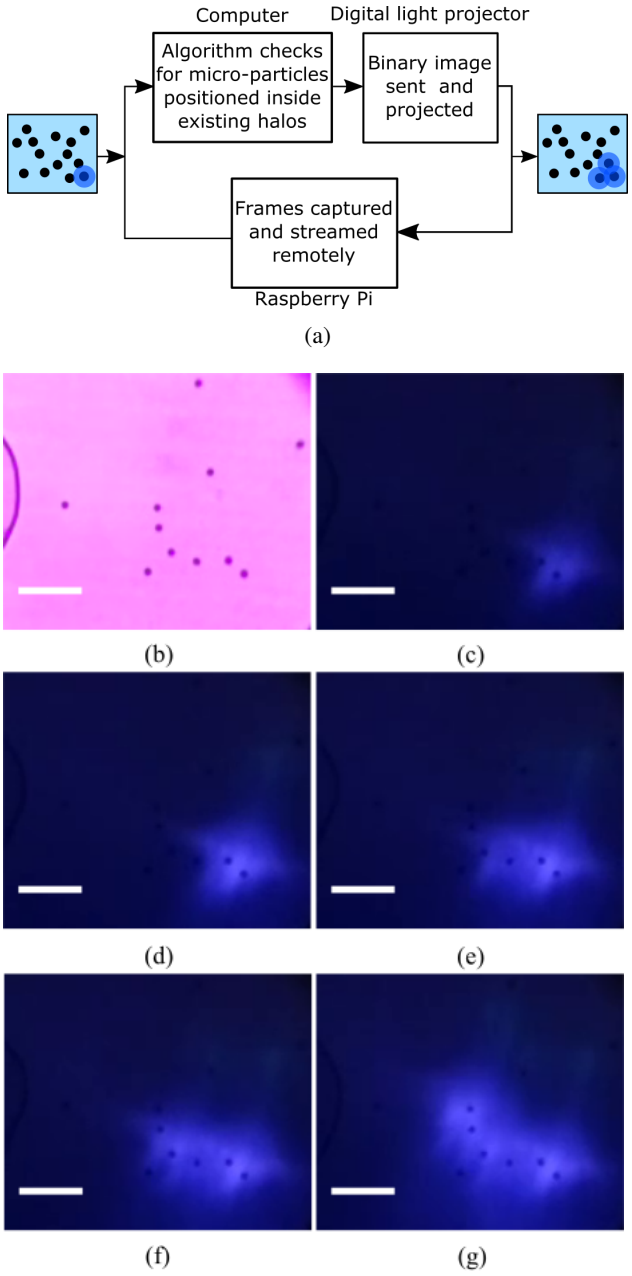

Fig. 5: (a) Closed-loop control strategy enabling feedback from the Raspberry Pi camera to the projector. (b)–(g) Propagation of an AR-based communication signal through a population of micro-particles. Starting from a random distribution of micro-particles (top left), we seed an "emmitting" micro-particle with a communication halo (top right). If this halo overlaps with another micro-particle, this micro-particle then also becomes an emitter. The following four images show the propagation of the communication signal using closed-loop AR. Scale bars represent a length of 80 μm.

References

[1] E. Şahin, "Swarm robotics: From sources of inspiration to domains of application," in *Swarm Robotics*, E. Şahin and W. M. Spears, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 10–20.

[2] A. F. T. Winfield, C. J. Harper, and J. Nembrini, "Towards dependable swarms and a new discipline of swarm engineering," in *Swarm Robotics*, E. Şahin and W. M. Spears, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 126–142.

[3] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intelligence*, vol. 7, no. 1, pp. 1–41, Mar 2013.

[4] T. O. Richardson and T. E. Gorochowski, "Beyond close-proximity interactions: the role of spatial coincidence in transmission networks," *Journal of the Royal Society Interface*, vol. 12, p. 20150705, 2015.

[5] A. Chakraborty and A. K. Kar, *Swarm Intelligence: A Review of Algorithms*. Cham: Springer International Publishing, 2017, pp. 475–494.

[6] S. Hauert and S. N. Bhatia, "Mechanisms of cooperation in cancer nanomedicine: towards systems nanotechnology," *Trends in Biotechnology*, vol. 32, no. 9, pp. 448 – 455, 2014, special Issue: Next Generation Therapeutics.

[7] J. Pascalie, M. Potier, T. Kowaliw, J.-L. Giavitto, O. Michel, A. Spicher, and R. Doursat, "Developmental design of synthetic bacterial architectures by morphogenetic engineering," *ACS Synthetic Biology*, vol. 5, no. 8, pp. 842–861, 2016.

[8] M. E. Taga and B. L. Bassler, "Chemical communication among bacteria," *Proceedings of the National Academy of Sciences*, vol. 100, no. suppl 2, pp. 14 549–14 554, 2003.

[9] J.-H. Park, G. von Maltzahn, L. L. Ong, A. Centrone, T. A. Hatton, E. Ruoslahti, S. N. Bhatia, and M. J. Sailor, "Cooperative nanoparticles for tumor detection and photothermally triggered drug delivery," *Advanced Materials*, vol. 22, no. 8, pp. 880–885, 2010.

[10] G. von Maltzahn, J.-H. Park, K. Y. Lin, N. Singh, C. Schwoeppe, R. M. Mesters, W. E. Berdel, E. Ruoslahti, M. J. Sailor, and S. N. Bhatia, "Nanoparticles that communicate in vivo to amplify tumour targeting." *Nature Materials*, vol. 10 7, pp. 545–52, 2011.

[11] T. E. Gorochowski and T. O. Richardson, "How behaviour and the environment influence transmission in mobile groups," in *Temporal Network Epidemiology. Theoretical Biology*, N. Masuda and P. Holme, Eds. Singapore: Springer, 2017.

[12] R. Raskar, G. Welch, and H. Fuchs, "Spatially augmented reality," in *First IEEE Workshop on Augmented Reality (IWAR'98)*, 1998, pp. 11–20.

[13] P. Mistry and P. Maes, "Sixthsense: a wearable gestural interface," in *ACM SIGGRAPH ASIA 2009 Sketches*. ACM, 2009, p. 11.

[14] R. K. Miyake, H. D. Zeman, F. H. Duarte, R. Kikuchi, E. Ramacciotti, G. Lovhoiden, and C. Vrancken, "Vein imaging: a new method of near infrared imaging, where a processed image is projected onto the skin for the enhancement of vein treatment," *Dermatologic surgery*, vol. 32, no. 8, pp. 1031–1038, 2006.

[15] G. Frangipane, D. Dell'Arciprete, S. Petracchini, C. Maggi, F. Saglimbeni, S. Bianchi, G. Vizsnyiczai, M. L. Bernardini, and R. Di Leonardo, "Dynamic density shaping of photokinetic *E. coli*," *eLife*, vol. 7, p. e36608, aug 2018.

[16] L. Fenno, O. Yizhar, and K. Deisseroth, "The development and application of optogenetics," *Annual Review of Neuroscience*, vol. 34, no. 1, pp. 389–412, 2011.

[17] Y. Gao, F. Mou, Y. Feng, S. Che, W. Li, L. Xu, and J. Guan, "Dynamic colloidal molecules maneuvered by light-controlled janus micromotors," *ACS Applied Materials & Interfaces*, vol. 9, no. 27, pp. 22 704–22 712, 2017.

[18] G. Vizsnyiczai, G. Frangipane, C. Maggi, F. Saglimbeni, S. Bianchi, and R. Di Leonardo, "Light controlled 3d micromotors powered by bacteria," *Nature Communications*, vol. 8, p. ncomms15974, 06 2017.

[19] C. Brieke, F. Rohrbach, A. Gottschalk, G. Mayer, and A. Heckel, "Light-controlled tools," *Angewandte Chemie International Edition*, vol. 51, no. 34, pp. 8446–8476, 2012.

[20] H. Eskandarloo, A. Kierulf, and A. Abbaspourrad, "Light-harvesting synthetic nano- and micromotors: a review," *Nanoscale*, vol. 9, pp. 12 218–12 230, 2017.

[21] P.-Y. Chiou, A. Ohta, and M. Wu, "Massively parallel manipulation of single cells and microparticles using optical images," *Nature*, vol. 436, pp. 370–2, 08 2005.

[22] S. M. Bartelt, J. Steinkühler, R. Dimova, and S. V. Wegner, "Light-guided motility of a minimal synthetic cell," *Nano Letters*, vol. 18, no. 11, pp. 7268–7274, 2018. [Online]. Available: https://doi.org/10.1021/acs.nanolett.8b03469

[23] G. Bradski, "The OpenCV Library," *Dr. Dobb's Journal of Software Tools*, 2000.

[24] E. B. Steager, D. Wong, N. Chodosh, and V. Kumar, "Optically addressing microscopic bioactuators for real-time control," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, May 2015, pp. 3519–3524.

[25] E. Pastrana, "Optogenetics: controlling cell function with light," *Nature Methods*, vol. 8, p. 24, 2010. [Online]. Available: https://doi.org/10.1038/nmeth.f.323

[26] M. Daly, M. Sergides, and S. Nic Chormaic, "Optical trapping and manipulation of micrometer and submicrometer particles," *Laser & Photonics Reviews*, vol. 9, no. 3, pp. 309–329, 2015.

[27] J. Katuri, X. Ma, M. M. Stanton, and S. Sánchez, "Designing micro- and nanoswimmers for specific applications," *Accounts of Chemical Research*, vol. 50, no. 1, pp. 2–11, 2017.

[28] M. Chalfie, Y. Tu, G. Euskirchen, W. W. Ward, and D. C. Prasher, "Green fluorescent protein as a marker for gene expression," *Science*, vol. 263, no. 5148, pp. 802–805, 1994.

[29] J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, C. Rueden, S. Saalfeld, B. Schmid, *et al.*, "Fiji: an open-source platform for biological-image analysis," *Nature Methods*, vol. 9, no. 7, p. 676, 2012.

[30] M. Crosscombe, J. Lawry, S. Hauert, and M. Homer, "Robust distributed decision-making in robot swarms: Exploiting a third truth state," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sep. 2017, pp. 4326–4332.

[31] I. Fister, I. Fister, X.-S. Yang, and J. Brest, "A comprehensive review of firefly algorithms," *Swarm and Evolutionary Computation*, vol. 13, pp. 34 – 46, 2013.

[32] H. Oh, A. R. Shirazi, C. Sun, and Y. Jin, "Bio-inspired self-organising multi-robot pattern formation: A review," *Robotics and Autonomous Systems*, vol. 91, pp. 83 – 100, 2017.

[33] H. Ceylan, J. Giltinan, K. Kozielski, and M. Sitti, "Mobile microrobots for bioengineering applications," *Lab Chip*, vol. 17, pp. 1705–1724, 2017.

[34] P. Molins and S. Hauert, "Trail formation in large robot swarms," in *The 34th ACM/SIGAPP Symposium On Applied Computing*. ACM/SIGAPP, 2019, p. in press.

[35] B. Dai, J. Wang, Z. Xiong, X. Zhan, W. Dai, C.-C. Li, S.-P. Feng, and J. Tang, "Programmable artificial phototactic microswimmer." *Nature Nanotechnology*, vol. 11 12, pp. 1087–1092, 2016.

[36] I. Slavkov, D. Carrillo-Zapata, N. Carranza, X. Diego, F. Jansson, J. Kaandorp, S. Hauert, and J. Sharpe, "Morphogenesis in robot swarms," *Science Robotics*, vol. 3, no. 25, 2018.